COHERENT constraints on Non-Standard neutrino Interactions

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with Danny Marfatia, based on work in [arXiv:1708.04255]

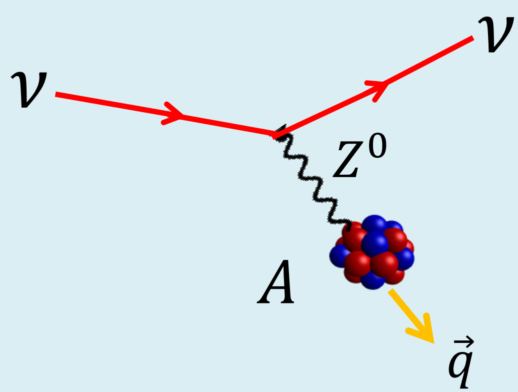
NUFACT 2017, Uppsala, Sweden, 09/30/2017

Outline

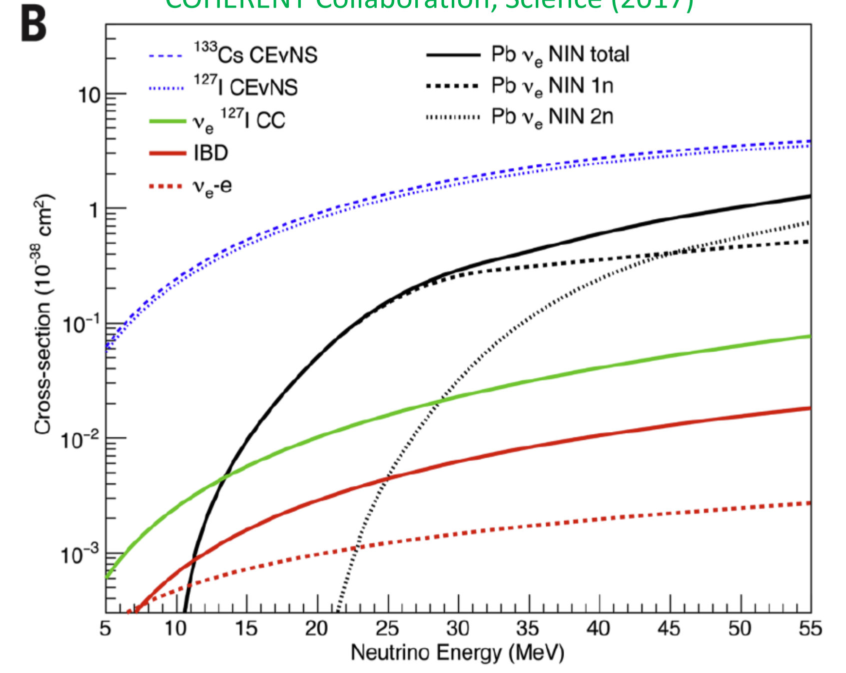
- Introduction
- COHERENT spectrum
- Constraints on NSI
- Summary

Coherent Elastic neutrino-Nucleus Scattering (CEvNS)

$Q \lesssim 1/R$



COHERENT Collaboration, Science (2017)



PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

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(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\boxed{\nu + A \to \nu + A}$ should have a sharp coherent forward peak just as $e + A \to e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm^2 on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \to \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

$\sigma_{SM} \propto N^2$

COHERENT experiment

pulsed

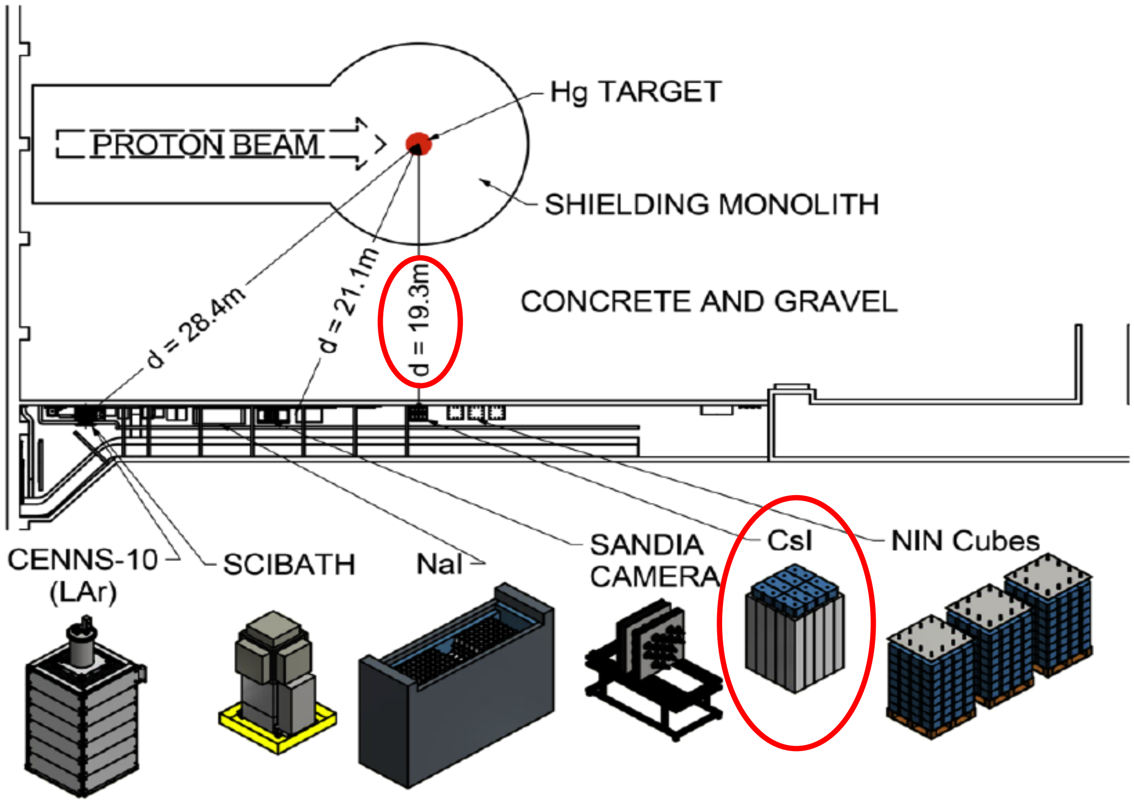


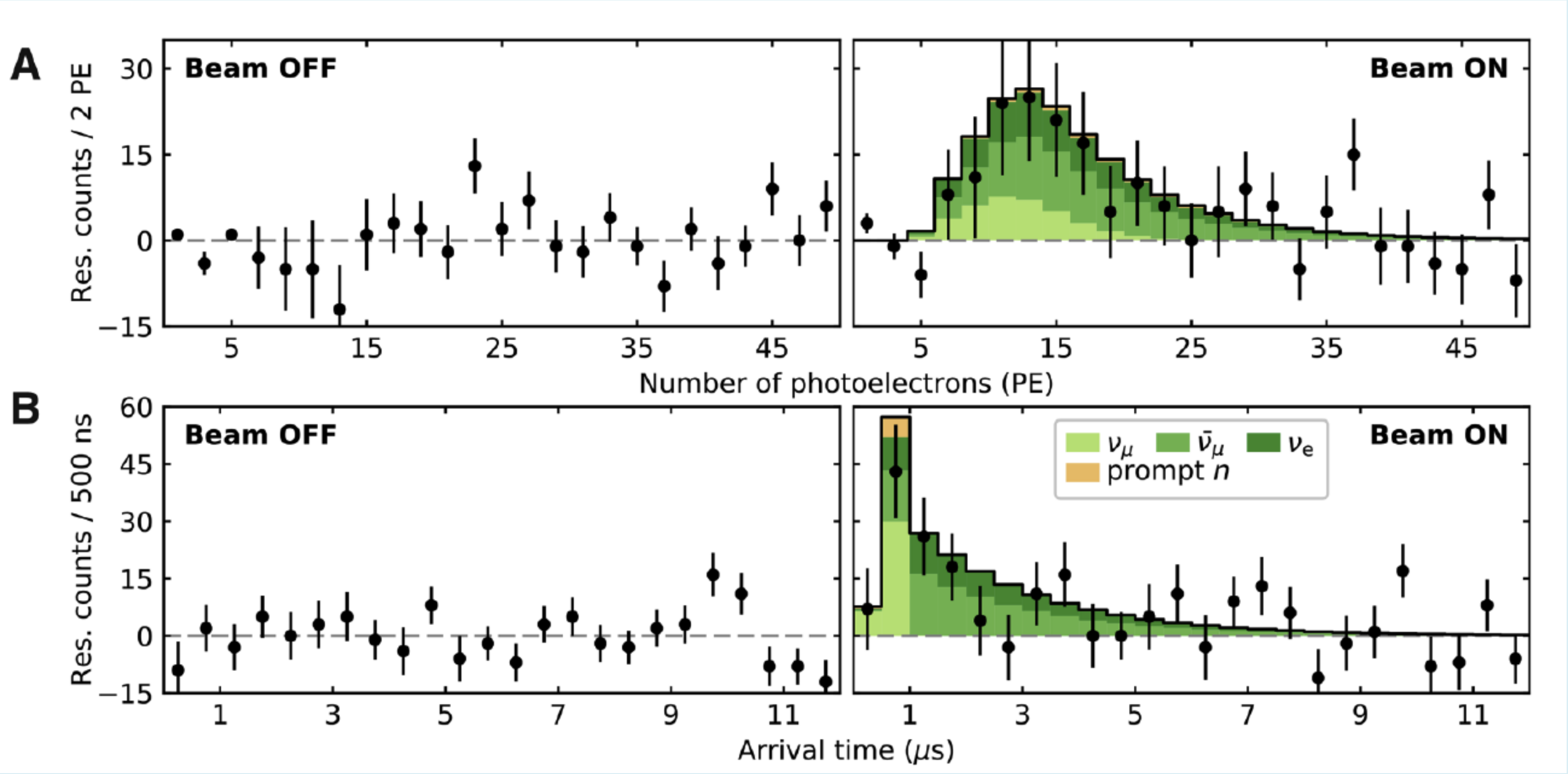
Fig. 2. COHERENT detectors populating the "neutrino alley" at the SNS (*34*). Locations in this basement corridor profit from more than 19 m of continuous shielding against beam-related neutrons, and a modest 8 m.w.e. overburden able to reduce cosmic-ray induced backgrounds, while sustaining an instantaneous neutrino flux as high as $1.7 \times 10^{11}\ \nu_\mu / \mathrm{cm}^2\ \mathrm{s}$.

COHERENT Collaboration, Science (2017)

COHERENT data

134 ± 22 events observed 173 ± 48 events predicted

6.7σ CL evidence for CEνNS



COHERENT Collaboration, Science (2017)

Simulation

Stopped π^- captured on target nuclei

Stopped π^+ decay at rest

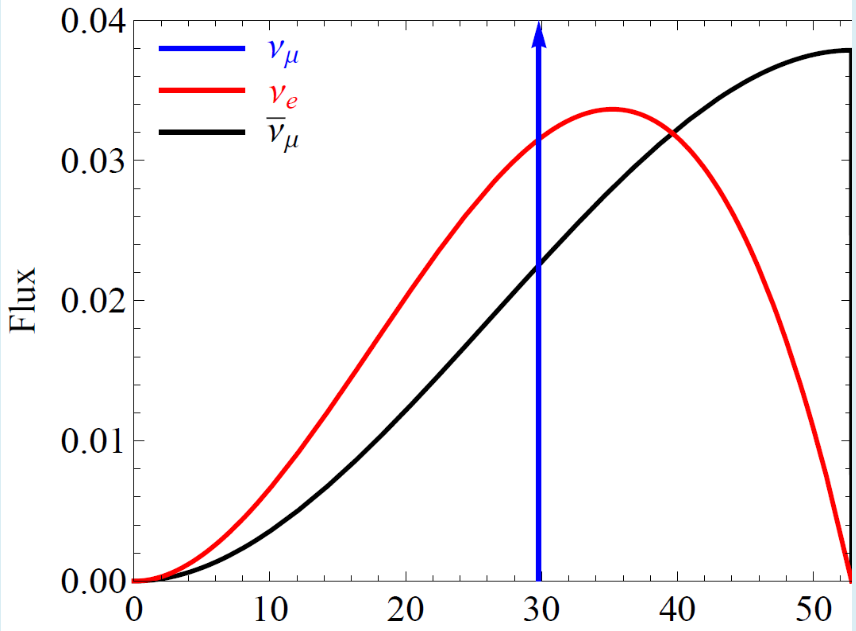
$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\hookrightarrow \mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

$$\phi_{\nu_\mu}(E_\nu) = \delta\left(E_\nu - \frac{m_\pi^2 - m_\mu^2}{2m_\pi}\right),$$

$$\phi_{\bar{\nu}_\mu}(E_\nu) = \frac{64E_\nu^2}{m_\mu^3}\left(\frac{3}{4} - \frac{E_\nu}{m_\mu}\right),$$

$$\phi_{\nu_e}(E_\nu) = \frac{192E_\nu^2}{m_\mu^3}\left(\frac{1}{2} - \frac{E_\nu}{m_\mu}\right),$$



$$\frac{d\sigma_\alpha}{dE_r} = \frac{G_F^2}{2\pi} Q_\alpha^2 F^2(2ME_r) M \left(2 - \frac{ME_r}{E_\nu^2}\right)$$

Effective charge in the SM

$$Q_{\alpha,\mathrm{SM}}^2 = \left(Z g_p^V + N g_n^V\right)^2$$

$$g_p^V = \frac{1}{2} - 2\sin^2\theta_W \qquad g_n^V = -\frac{1}{2}$$

Nuclear form factor

$$F(q = \sqrt{2ME_r}) = \frac{4\pi\rho_0}{Aq^3}\left[\frac{\sin(qR_A) - qR_A\cos(qR_A)}{1 + a^2q^2}\right]$$

Klein and Nystrand, Phys. Rev. Lett. 84, 2330 (2000)

$$N_\alpha^i = \frac{rN_{\mathrm{POT}}}{4\pi L^2} \times \frac{2m_{\mathrm{det}}}{M_{\mathrm{CsI}}} N_A \times \int dn_{\mathrm{PE}} f(n_{\mathrm{PE}}) \frac{dE_r}{dn_{\mathrm{PE}}} \int dE_\nu \phi_\alpha(E_\nu) \frac{d\sigma_\alpha}{dE_r}(E_\nu, E_r)$$

$r = 0.08$ is the number of neutrinos per favor for each proton on target

$N_{POT} = 1.76 \times 10^{23}$ is the total number of protons delivered to the target

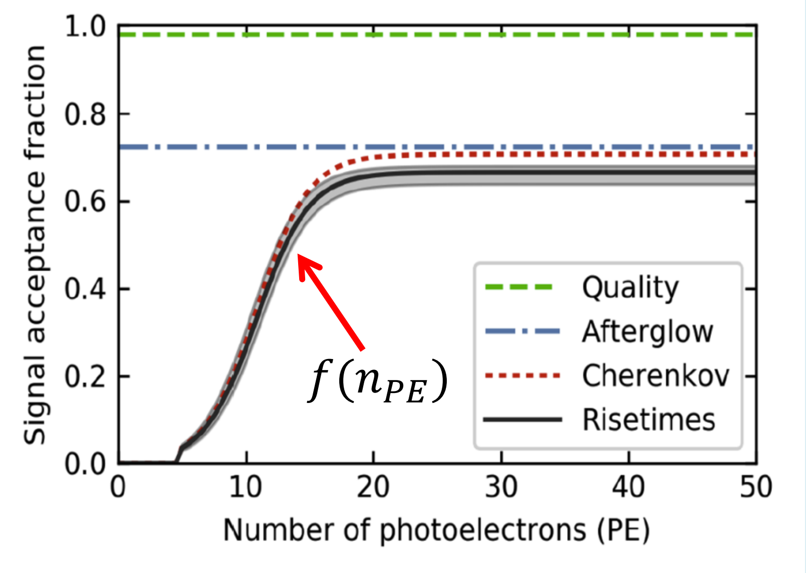
$L = 19.3$ m is the distance between the source and the CsI detector

$m_{det} = 14.6$ kg is the mass of detector, M_{CsI} is the molar mass of CsI

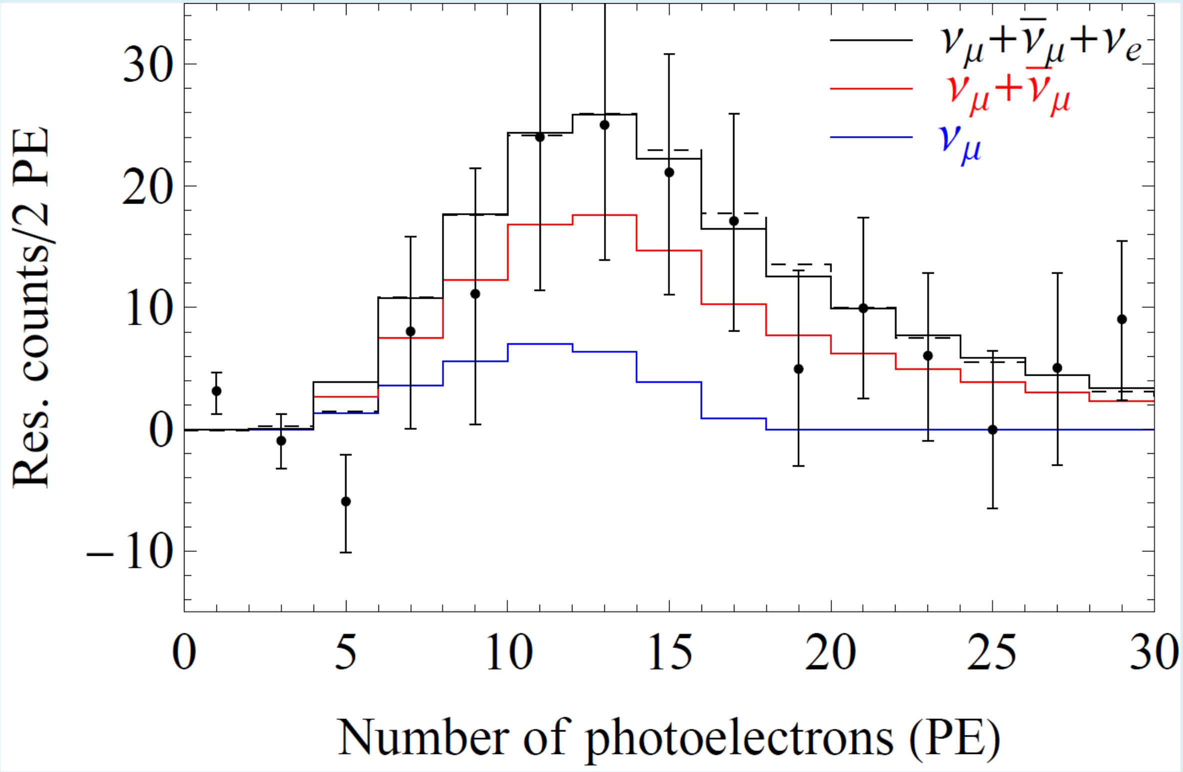
"Approximately 1.17 photoelectrons are expected per keV of cesium or iodine nuclear recoil energy"

$$n_{\mathrm{PE}} = 1.17 \left(\frac{E_r}{\mathrm{keV}} \right)$$

COHERENT Collaboration, Science (2017)



SM spectrum



Sterile neutrinos: Anderson et al. 2012; Dutta et al. 2015; Kosmas et al. 2017

Neutrinos magnetic moment: Dodd et al. 1991; Scholberg 2005; Kosmas et al. 2015

Light dark matter: deNiverville et al. 2015

Nonstandard neutrino interactions: Barranco et al. 2005, 2007; Scholberg 2005; Dutta et al. 2015; Lindner et al. 2016; Dent et al. 2016; Coloma et al. 2017; Shoemaker 2017

see also COHERENT Collaboration, Science (2017), Coloma et al. 1708.02899

Matter NSI

Neutral current

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F \sum_{\alpha\beta fC} \epsilon_{\alpha\beta}^{fC} \left[\bar{\nu}_{\alpha L}\gamma^\rho \nu_{\beta L}\right]\left[\bar{f}\gamma_\rho P_C f\right]$$

Wolfenstein, Phys. Rev. D 17, 2369 (1978)

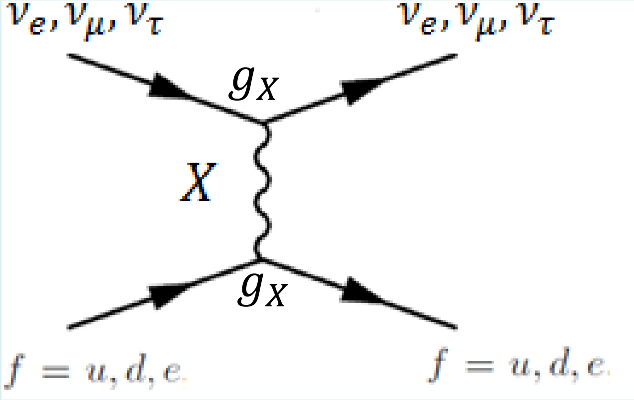
$$\alpha,\beta = e,\mu,\tau,\; C = L,R,\; f = u,d,e$$

Only vector part contributes to the effective potential

$$\mathcal{L}_{\rm NSI} = -\sqrt{2}G_F \epsilon_{\alpha\beta}^{fV} \left[\bar{\nu}_{\alpha L}\gamma^\rho \nu_{\beta L}\right]\left[\bar{f}\gamma_\rho f\right]$$

$$\epsilon_{\alpha\beta}^{fV} \equiv \epsilon_{\alpha\beta}^{fL} + \epsilon_{\alpha\beta}^{fR}$$

Coherent forward scattering $q^2 \to 0$



$$q^2 \ll m_X^2$$

$$\varepsilon \propto \frac{g_X^2 m_W^2}{m_X^2}$$

Farzan, Phys. Lett. B748, 311 (2015)

Light mediator, $m_X \sim 10$ MeV, $g_X \sim 10^{-5}$, $\varepsilon \sim O(1)$

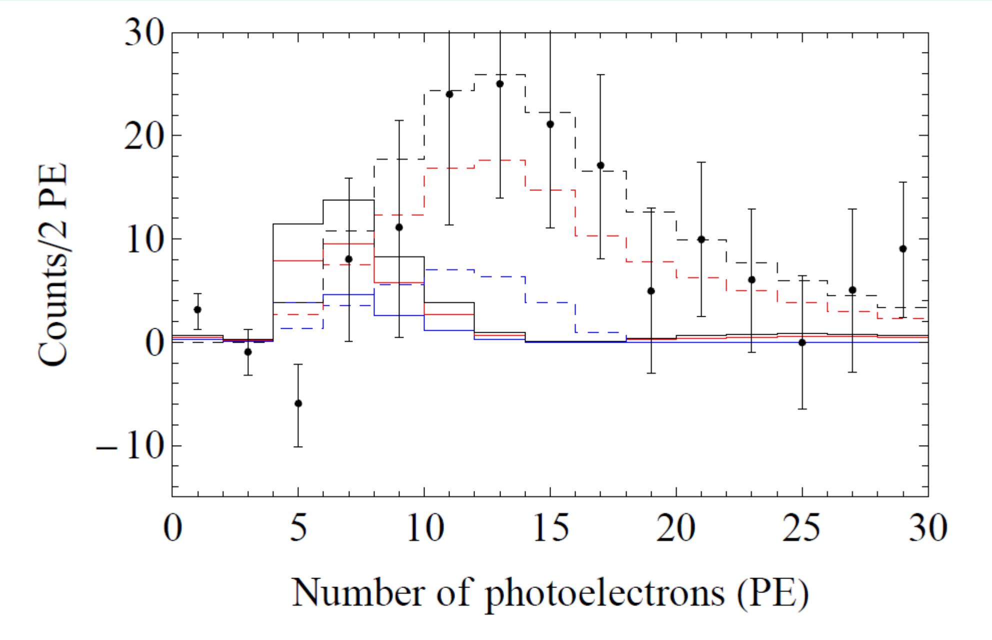
Light mediator

A purely vector mediator

$$\mathcal{L}_{\mathrm{NSI}} = -g\left(\bar{\nu}\gamma^\rho\nu + \bar{\mu}\gamma^\rho\mu + \bar{u}\gamma^\rho u + \bar{d}\gamma^\rho d\right) Z'_\rho$$

Modified effective charge

$$Q^2_{\alpha,\mathrm{NSI}} = \left[Z\left(g_p^V + \frac{3g^2}{2\sqrt{2}G_F(Q^2 + M_{Z'}^2)}\right) + N\left(g_n^V + \frac{3g^2}{2\sqrt{2}G_F(Q^2 + M_{Z'}^2)}\right)\right]^2$$



Moment transfer

$$Q^2 = 2ME_r$$

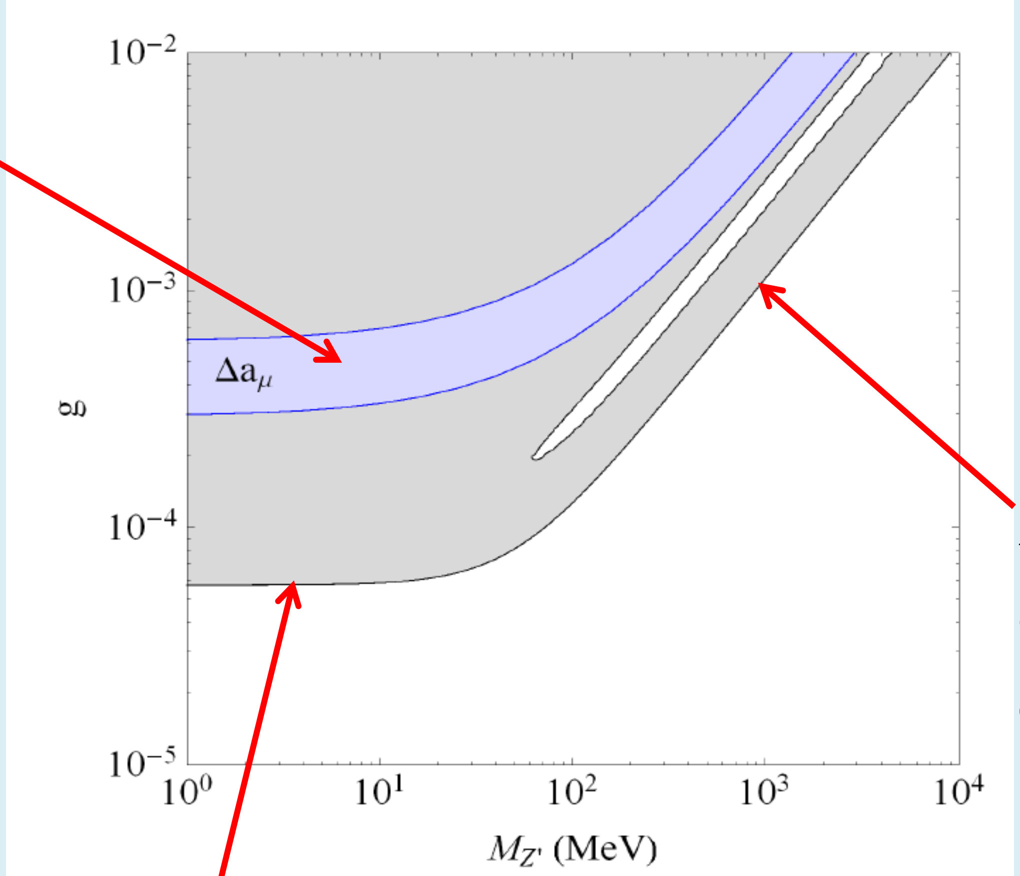
$$M_{Z'} = 10 \text{ MeV and } g = 10^{-4}$$

$$\chi^2 = \sum_i \left[\frac{N^i_{\rm exp} - N^i_{\rm NSI}(1+\alpha)}{\sigma^i_{\rm stat}}\right]^2 + \left(\frac{\alpha}{\sigma_\alpha}\right)^2$$

12 bins, 6≤PE<30

$\sigma_\alpha = 0.28$

Explains Δa_μ at 2σ



Propagator

NSI ∝ $\frac{g^2}{2ME_r + M^2_{Z'}}$

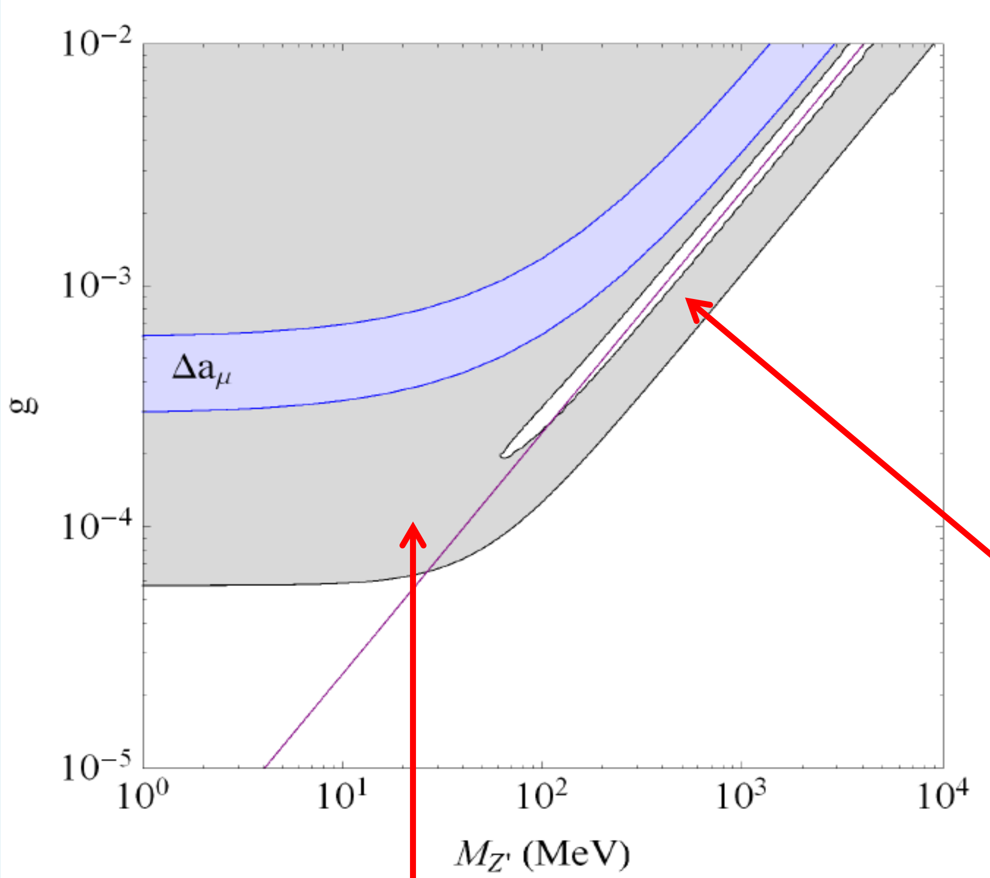
For heavy mediators, i.e., $M_{Z'} \gg \sqrt{2ME_r}$, the limit depends on $\frac{g^2}{M^2_{Z'}}$ and can constrain NSI matter effect

For very light mediators, i.e., $M_{Z'} < 50$ MeV, the limit is only sensitive to g, while the NSI matter effect is sensitive to $\frac{g^2}{M^2_{Z'}}$, hence the COHERENT constraint does not apply to matter NSI induced by a very light mediator.

$$\chi^2 = \sum_i \left[\frac{N^i_{\rm exp} - N^i_{\rm NSI}(1+\alpha)}{\sigma^i_{\rm stat}} \right]^2 + \left(\frac{\alpha}{\sigma_\alpha} \right)^2$$

12 bins, 6≤PE<30

$$\sigma_\alpha = 0.28$$



Propagator

$$\text{NSI} \propto \frac{g^2}{2ME_r + M^2_{Z'}}$$

$$Q_{\alpha,\rm NSI} = -Q_{\alpha,\rm SM}$$

$$\frac{g^2}{M^2_{Z'}} = -\frac{4\sqrt{2}(Zg^V_p + Ng^V_n)}{3(Z+N)} G_F$$

For very light mediator, modification of the spectral shapes breaks the degeneracy.

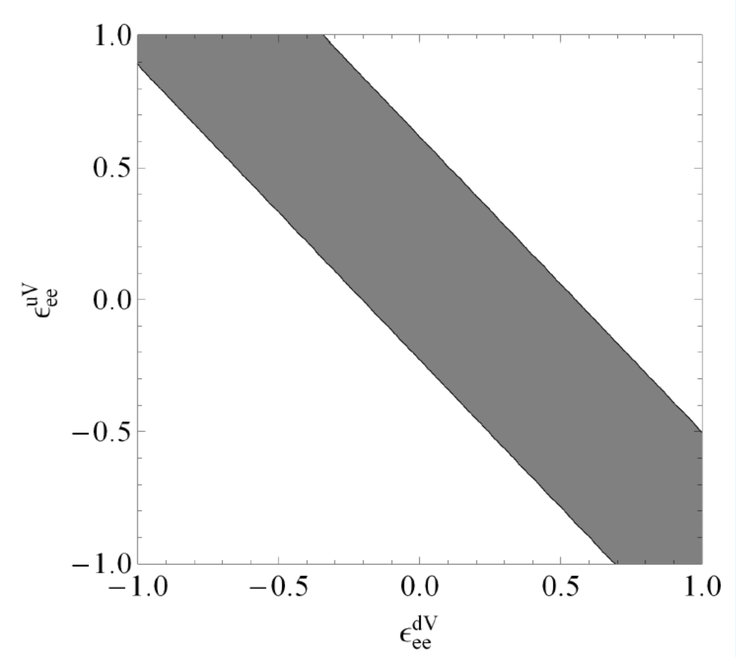
Heavy mediator

$$\mathcal{L}_{\rm NSI} = -\sqrt{2} G_F \epsilon^{fV}_{\alpha\beta} \left[\overline{\nu}_{\alpha L}\gamma^\rho \nu_{\beta L}\right]\left[\bar{f}\gamma_\rho f\right]$$

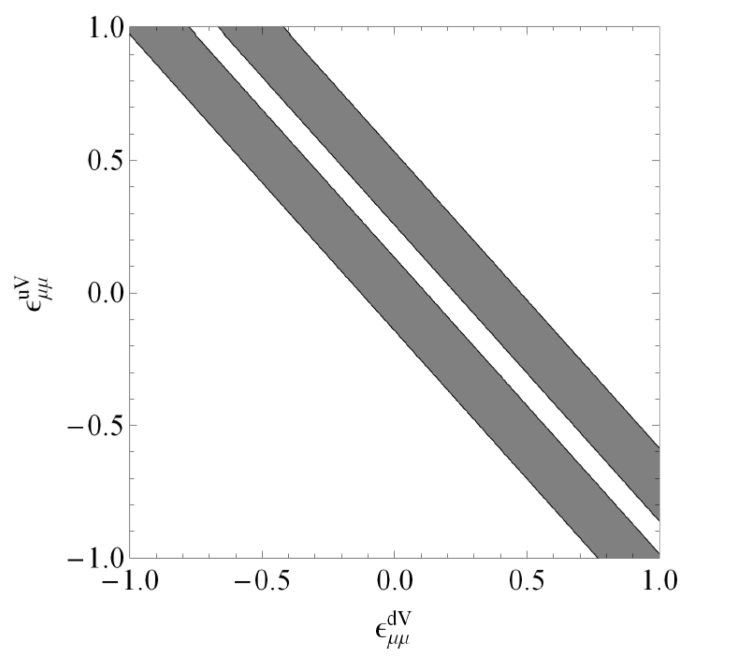
$$Q^2_\alpha = \left[Z(g_p^V + 2\epsilon^{uV}_{\alpha\alpha} + \epsilon^{dV}_{\alpha\alpha}) + N(g_n^V + \epsilon^{uV}_{\alpha\alpha} + 2\epsilon^{dV}_{\alpha\alpha})\right]^2 + \sum_{\beta\neq\alpha}\left[Z(2\epsilon^{uV}_{\alpha\beta} + \epsilon^{dV}_{\alpha\beta}) + N(\epsilon^{uV}_{\alpha\beta} + 2\epsilon^{dV}_{\alpha\beta})\right]^2 .$$

Real $\epsilon^f_{\alpha\beta}$

(a) $\epsilon^{uV}_{ee} \neq 0,\ \epsilon^{dV}_{ee} \neq 0.$



(b) $\epsilon^{uV}_{\mu\mu} \neq 0,\ \epsilon^{dV}_{\mu\mu} \neq 0.$



$$Z g_p^V + N g_n^V = \pm\left[Z(g_p^V + 2\epsilon^{uV}_{\alpha\alpha} + \epsilon^{dV}_{\alpha\alpha}) + N(g_n^V + \epsilon^{uV}_{\alpha\alpha} + 2\epsilon^{dV}_{\alpha\alpha})\right]$$

Two Linear bands

Scholberg, Phys. Rev. D 73, 033005 (2006)

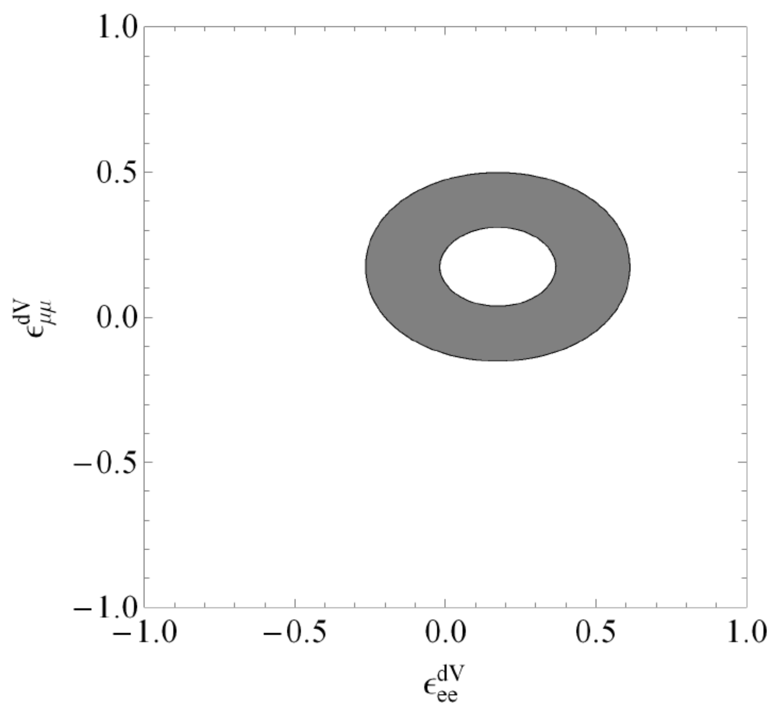
Heavy mediator

$$\mathcal{L}_{\rm NSI} = -\sqrt{2} G_F \epsilon^{fV}_{\alpha\beta} \left[\overline{\nu}_{\alpha L} \gamma^\rho \nu_{\beta L}\right] \left[\bar{f} \gamma_\rho f\right]$$

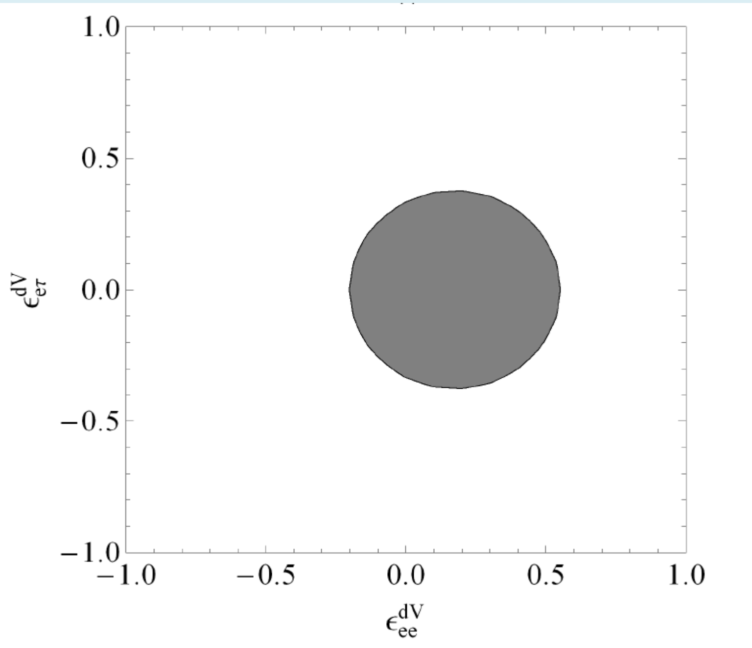
$$Q^2_\alpha = \left[Z(g_p^V + 2\epsilon^{uV}_{\alpha\alpha} + \epsilon^{dV}_{\alpha\alpha}) + N(g_n^V + \epsilon^{uV}_{\alpha\alpha} + 2\epsilon^{dV}_{\alpha\alpha})\right]^2 + \sum_{\beta\neq\alpha} \left[Z(2\epsilon^{uV}_{\alpha\beta} + \epsilon^{dV}_{\alpha\beta}) + N(\epsilon^{uV}_{\alpha\beta} + 2\epsilon^{dV}_{\alpha\beta})\right]^2 .$$

Real $\epsilon^f_{\alpha\beta}$

(c) $\epsilon^{dV}_{ee} \neq 0,\ \epsilon^{dV}_{\mu\mu} \neq 0.$



(d) $\epsilon^{dV}_{ee} \neq 0,\ \epsilon^{dV}_{e\tau} \neq 0.$



$$\left(Zg_p^V + Ng_n^V\right)^2 = \left[Z(g_p^V + \epsilon^{dV}_{ee}) + N(g_n^V + 2\epsilon^{dV}_{ee})\right]^2 + \left[Z\epsilon^{dV}_{e\tau} + 2N\epsilon^{dV}_{e\tau}\right]^2$$

Effective NSI parameters

SM

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m_{21}^2 & 0\\ 0 & 0 & \Delta m_{31}^2\end{pmatrix}U^\dagger + A\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}\\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

Effective parameters

$$\epsilon_{\alpha\beta} \equiv \sum_f \epsilon_{\alpha\beta}^{fV}\frac{N_f}{N_e}$$

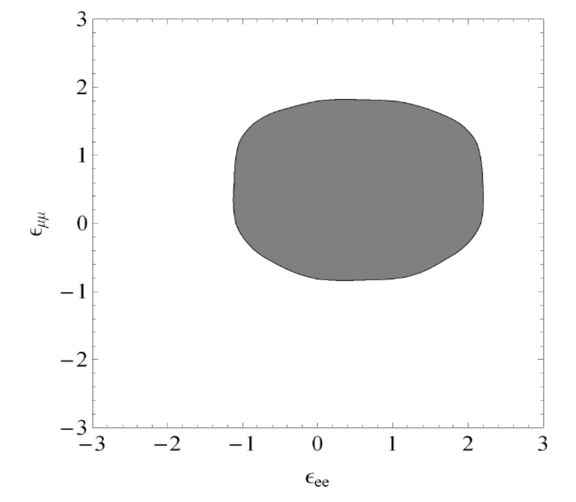
$$A \equiv 2\sqrt{2}G_F N_e E$$

On earth $N_u = N_d = 3N_e$

$$\epsilon_{\alpha\alpha} \approx 3(\epsilon_{\alpha\alpha}^{uV} + \epsilon_{\alpha\alpha}^{dV})$$

$$-0.95 \le \epsilon_{ee} \le 1.95\,, \qquad -0.66 \le \epsilon_{\mu\mu} \le 1.57\,.$$

At 90% CL



Break the generalized MH degeneracy; see Peter's talk

$$\Delta m_{31}^2 \to -\Delta m_{32}^2$$
$$\sin\theta_{12} \leftrightarrow \cos\theta_{12}$$
$$\delta \to \pi - \delta$$

$$\epsilon_{ee} \to -\epsilon_{ee} - 2\,,$$
$$\epsilon_{\alpha\beta} \to -\epsilon_{\alpha\beta}^* \quad (\alpha\beta \ne ee)$$

Same oscillation probabilities

Coloma, Schwetz [1604.05772]

Summary

We analyzed the COHERENT spectrum to constrain NSI.

- For a lighter mediator, COHERENT data only constrain the mediator coupling, and it does not apply to matter NSI induced by a very light mediator.
- For a heavier mediator, the COHERENT constraints are weakened by degeneracies between different combinations of NSI parameters. However, the data can still place meaningful constraints on the effective NSI parameters in Earth matter since they depend on the sum of the up-type and down-type NSI parameters.

Thank you!

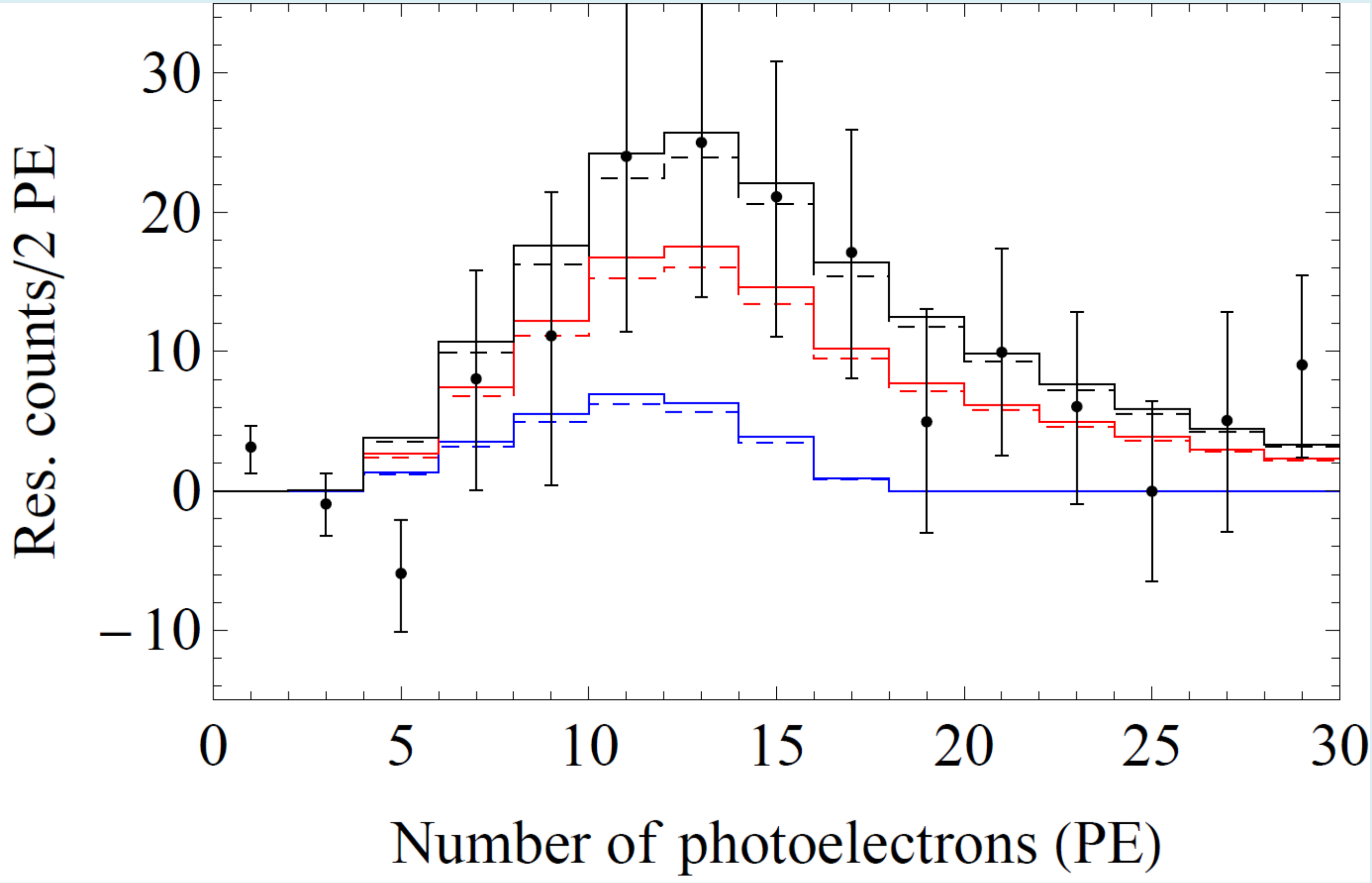
Backup slides

Global Analysis

Gonzalez-Garcia, Maltoni [1307.3092]

		90% CL		3σ	
Param.	best-fit	LMA	LMA $\oplus$ LMA-D	LMA	LMA $\oplus$ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$+0.298$	$[+0.00, +0.51]$	$\oplus\ [-1.19, -0.81]$	$[-0.09, +0.71]$	$\oplus\ [-1.40, -0.68]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$+0.001$	$[-0.01, +0.03]$	$[-0.03, +0.03]$	$[-0.03, +0.20]$	$[-0.19, +0.20]$
$\varepsilon^u_{e\mu}$	-0.021	$[-0.09, +0.04]$	$[-0.09, +0.10]$	$[-0.16, +0.11]$	$[-0.16, +0.17]$
$\varepsilon^u_{e\tau}$	$+0.021$	$[-0.14, +0.14]$	$[-0.15, +0.14]$	$[-0.40, +0.30]$	$[-0.40, +0.40]$
$\varepsilon^u_{\mu\tau}$	-0.001	$[-0.01, +0.01]$	$[-0.01, +0.01]$	$[-0.03, +0.03]$	$[-0.03, +0.03]$
ε^u_D	-0.140	$[-0.24, -0.01]$	$\oplus\ [+0.40, +0.58]$	$[-0.34, +0.04]$	$\oplus\ [+0.34, +0.67]$
ε^u_N	-0.030	$[-0.14, +0.13]$	$[-0.15, +0.13]$	$[-0.29, +0.21]$	$[-0.29, +0.21]$
$\varepsilon^d_{ee} - \varepsilon^d_{\mu\mu}$	$+0.310$	$[+0.02, +0.51]$	$\oplus\ [-1.17, -1.03]$	$[-0.10, +0.71]$	$\oplus\ [-1.44, -0.87]$
$\varepsilon^d_{\tau\tau} - \varepsilon^d_{\mu\mu}$	$+0.001$	$[-0.01, +0.03]$	$[-0.01, +0.03]$	$[-0.03, +0.19]$	$[-0.16, +0.19]$
$\varepsilon^d_{e\mu}$	-0.023	$[-0.09, +0.04]$	$[-0.09, +0.08]$	$[-0.16, +0.11]$	$[-0.16, +0.17]$
$\varepsilon^d_{e\tau}$	$+0.023$	$[-0.13, +0.14]$	$[-0.13, +0.14]$	$[-0.38, +0.29]$	$[-0.38, +0.35]$
$\varepsilon^d_{\mu\tau}$	-0.001	$[-0.01, +0.01]$	$[-0.01, +0.01]$	$[-0.03, +0.03]$	$[-0.03, +0.03]$
ε^d_D	-0.145	$[-0.25, -0.02]$	$\oplus\ [+0.49, +0.57]$	$[-0.34, +0.05]$	$\oplus\ [+0.42, +0.70]$
ε^d_N	-0.036	$[-0.14, +0.12]$	$[-0.14, +0.12]$	$[-0.28, +0.21]$	$[-0.28, +0.21]$

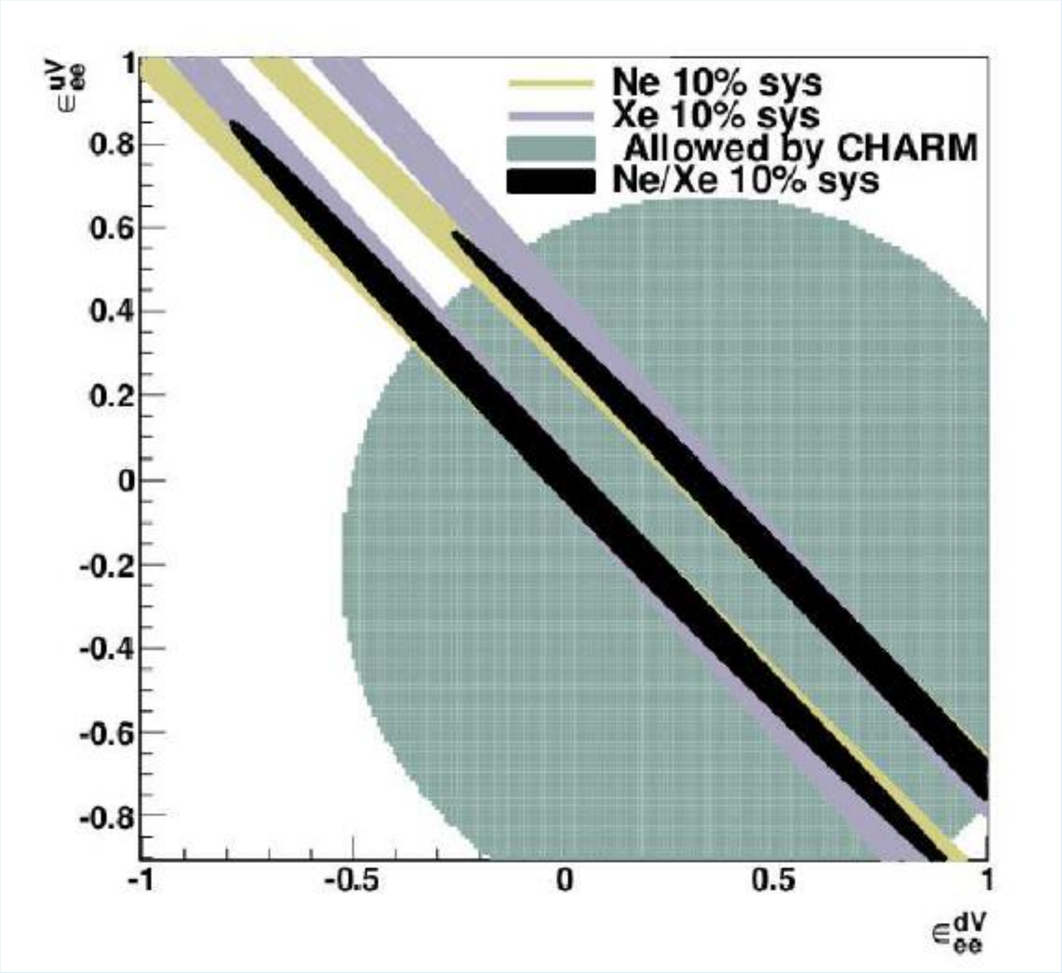
Sterile neutrinos



$\Delta m^2_{41} = 1.75\ eV^2$, $|U_{e4}| = 0.164$, $|U_{\mu 4}|$=0.119

Collin et al. Phys. Rev. Lett. 117, 221801 (2016)

Multiple elements



Scholberg, Phys. Rev. D 73, 033005 (2006)